National Aeronautics and Space Administration

SEARCH FOR EARTH-LIKE PLANETS STRATEGIC ROADMAP COMMITTEE

February 15–16, 2005

Westward Look Hotel
245 E. Ina Road
Tucson, Arizona

MEETING REPORT

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Ghassem Asrar
Co-Chair

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Adam Burrows
Co-Chair

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Charles Beichman
Co-Chair

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Eric Smith
Designated Federal Official

Search for Earth-like Planets Strategic Roadmap Committee
February 15–16, 2005
Westward Look Hotel
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CONTENTS

Meeting Report Prepared by:
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Tuesday, February 15

Meeting Opening

Dr. Eric Smith, the Designated Federal Official for the Search for Earth-Like Planets Strategic Roadmap (SRM) Committee opened the meeting at 9:00 a.m. He noted that the meeting was being conducted under the rules of the Federal Advisory Committee Act (FACA) and explained the rules under which visitors would be allowed to address the committee. He then summarized the rules for members to recuse themselves from specific discussions, to avoid conflicts of interest on matters that might arise during the meeting.

Objectives, Charter, and Expectations

Dr. Ghassem Asrar, a co-chair of the committee and Deputy Associate Administrator in the Science Mission Directorate (SMD), described the roles of the three co-chairs and NASA's general expectations for the strategic roadmaps. The roadmaps collectively will define the direction of Agency activities for a time frame extending over the next three decades. Legacy roadmapping activities, community priorities set through the National Research Council (NRC) decadal reviews, and other authoritative sources will be used as input to the roadmapping process. The interrelationships between the roadmaps are being handled through active interfaces between the committees and their staffs. NASA will use the products from the roadmap committees as the foundation for the guidance it issues when presenting and explaining its budget requests and for reporting on the status of programs and projects.

Dr. Adam Burrows, also a committee co-chair, thanked the members for their willingness to participate. He noted that this roadmapping exercise is not beginning from the ground level. It has many documents to use as input, but the committee is not constrained to include particular elements of any past plans. The role of the committee is to establish a roadmap consistent with NASA's strategic objectives and the President's Vision for U.S. Space Exploration, as announced in January 2004 and explicated through the report of the President's Commission on Implementation of United States Space Exploration Policy (Aldridge Commission).

Dr. Charles Beichman, the third committee co-chair, said that the search for Earth-like planets has now made it to the top of the political agenda, 2000 years after the Roman philosopher Lucretius first wrote about multiple worlds like ours. Dr. Beichman stressed the importance of mapping out the best possible program, one that moves quickly but efficiently to achieve capabilities necessary for finding and characterizing Earth-like planets.

In answer to a question on the time horizon for the roadmap, the co-chairs said that the vision for the planet-finding program should extend broadly, even if the detailed planning for missions and investigations does not go out that far. At the chairs' request, the members introduced themselves briefly, followed by introduction of the NASA ex officio members present. The members then gave their responses to one or more of three topical questions posed to them before the meeting for their consideration:

1. What will the science of Earth-like planet detection/characterization be in 2035?

2. What constitutes an "advanced telescope" in a post-TPF [Terrestrial Planet Finder] world?
3. What are the necessary elements (science products/milestones) for this roadmap in order for it to be sustainable over this long time frame?

Dr. Victoria Meadows said that, by 2035, she expects that the Space Interferometry Mission (SIM) and the Terrestrial Planet Finder–Coronagraph (TPF-C) and Terrestrial Planet Finder–Interferometer (TPF-I) missions will have flown. Terrestrial planets will have been found, and preliminary characterization of them performed. The science of comparative planetology, which is currently confined to planets in our own solar system, will have expanded to include perhaps a hundred terrestrial planets. We will know the masses of these extrasolar terrestrial planets, will have detected some seasonal differences, and will have classified them according to compositional characteristics. Although the first reconnaissance will have been made, temporal resolution will still be on the order of months, and spectral resolution will be sufficiently low that classification based on a full set of planetary characteristics will be extremely difficult. Dr. Meadows went on to describe what might be the state of knowledge about planetary evolution and the expansion of understanding of the Sun–Earth connection to star–planetary system relationships in general, particularly habitability and the chemical balance of terrestrial planets. With respect to advanced telescopes, Dr. Meadows asked for very large collecting area and higher spectral and temporal resolution, including ultimately hyperspectral imaging with much higher angular resolution (to enable spatial resolution on a target planet). She discussed the relevance of her desired features to characterizing habitability of exoplanets, detecting indicators of life, and, looking far beyond 2035, life characterization.

Mr. Gerald Chodil's vision for 2035 included successful flights of the Kepler, SIM, TPF-C, and TPF-I missions. However, a "Life Finder" mission will not yet have flown. He summarized what each of the flown missions will have achieved in identifying and characterizing planetary systems in the galactic neighborhood and at greater intergalactic distances. Habitability of some of these systems will be characterized, but Mr. Chodil distinguished habitability from knowing whether any of the exoplanets were inhabited. There will be a good model of planetary evolution that can account for a range of planetary systems, including those that differ from our solar system. With respect to advanced telescopes, he expects formation flying to enable large, sparse apertures, including capabilities to upgrade, improve, and repair aperture components. Modeling capability to support on-orbit calibration will be essential because these large systems will not be capable of calibration on the ground. Observing systems located at either the L1 or L2 libration points will be repairable, with human involvement in assembly and repair missions likely. In response to the question about sustaining the roadmap activities over the long term, Mr. Chodil emphasized the need to convince the public, the Congress, and successive administrations that continued investment is truly worth doing and that planet-finding deserves the same degree of national commitment that is now being given to human exploration. He suggested that the committee consider ways to fill in the gaps in the current series of planned major missions with some smaller programs, which would help the technology to progress while producing some incremental science. This will help to sustain interest, both from the public and in the community of expertise needed to prepare for and operate the missions.

Dr. Beichman agreed with Mr. Chodil on the importance of a planet-finding program that incorporates multiple scales, small and large, at which interesting and important science is done. He described how that has in fact been the pattern in the recent past, with discoveries from radial velocity investigations, from the Hubble Space Telescope (HST) and the Spitzer Space Telescope. Maintaining a mix of large and small programs, on the ground and in space, is vital.

Dr. Beichman agreed with Dr. Meadows that a long-term science vision, with the technology development to support it, is critical. He suggested that the vision for 2035 she had presented would make an excellent initial draft for the introduction to the roadmap. Several members commented on the ease with which planet-finding can capture the imagination and interest of the lay public.

Dr. Frank Martin deferred to the other members on the vision for 2035. With respect to how to sustain the program and the funding for it, selling the program to Congress and the American people is essential. He cited *Cosmic Discovery: The Search, Scope, and Heritage of Astronomy*, by Martin Harwit [ISBN: 0262580683], to illustrate the importance of looking for large opportunities and the potential for major discoveries. To sustain a progression of results and discoveries, the program should have a combination of big observatories, which open up new areas, and incremental improvements through smaller missions. Dr. Martin also stressed the importance of getting the near-term program right; otherwise, the longer term plans will become irrelevant.

Dr. John Mather said that, with respect to detection of Earth-like planets in 2035, a great deal will be known about giant planets in other systems, but Earth-like planets will be harder to find. He expects there will be signs of life (past or extant) found on Mars and Jovian satellites in our own solar system. Astrobiology will be a lively discipline, with real data over which people can argue. Part of the task for education and public outreach (E/PO) will be to keep planet finding, astrobiology, and astronomy competitive with biotechnology in capturing the interest of the next generation of science-oriented students. On the topic of advanced telescopes, he agreed that very large telescopes will be important in the post-TPF world. To observe planets in distant planetary systems will require capturing "sparse photons." He anticipates that support in developing the capability for these very large aperture observing systems will come from the Department of Defense (DoD) and the National Reconnaissance Office (NRO). He agreed with other members' comments on the importance of having important results coming out every year, rather than relying on a few huge projects.

Ms. Maureen Heath's vision for the status of planet-finding in 2035 was that SIM, the TPF missions, and ground-based searches will have provided a complete survey of the galactic neighborhood near our own solar system. The number of stars with jovian-type planets will be known, and some rocky planets will have been characterized. By 2035, she expects there will be a couple of good candidates for Earth-like planets, which investigators will be anxious to study further. It will be a period of human exploration of destinations like Mars proceeding in parallel with extrasolar exploration [using observing systems]. She noted the point Mr. Chodil had made about the potential role for manned missions to service and repair large observatories at deep space locations such as the libration points. She agreed with the other members' comments about large-aperture telescopes in the post-TPF world. By 2035, we should be experts at on-orbit assembly to make such systems feasible. She agreed with Dr. Martin's point about the program needing a series of building blocks to remain sustainable. In line with the DoD concept of spiral development, earlier missions should provide technology development and risk reduction for subsequent missions. Having too much of the program's science objectives hanging on the success of a single mission would be a dangerous approach.

Dr. Beichman spoke about the supporting role of the James Webb Space Telescope (JWST) in helping to understand the conditions about the universe that make it capable of generating and sustaining life. This larger context for the search for Earth-like planets will be important for questions about how we live in a habitable universe. Because of this supporting role, JWST is relevant to the planet-finding roadmap.

With respect to Dr. Mather's comments on astrobiology, Mr. Chodil asked if the committee should focus on water as the liquid medium essential to support life, or are other liquids such as ammonia or methane potential liquid media for life. Dr. Meadows responded that water is the starting point for Earth-like habitability, and life-characterization searches should begin by designing to that assumption. However, astrobiology cannot be restricted to considering only water-mediated life systems. These comments led to further discussion of how the issue of the liquid medium for life processes ties into design requirements for life detection and characterization investigations.

Dr. Burrows iterated Ms. Heath's point that the push for exploration is not just human exploration of the solar system. The roadmap needs to emphasize that exploration encompasses the type of exploration beyond the solar system represented by the planet-finding program.

Dr. Tom Greene's response to the question on the status of planet-finding in 2035 was that there would be information on particular planet types from surveys and some very detailed information on a subset of planets identified by the surveys. Ground-based multi-conjugated astronomical observatories will have been in operation, in addition to the NASA missions (Kepler, JWST, SIM, and the TPF missions). JWST will provide information on how planets form around stars. An interesting science problem will be predicting, from conditions in a protoplanetary disk, what kinds of planets will form and which will have the chemical precursors for life. On the topic of advanced telescopes, Dr. Greene said that space-based observing systems will still be needed for the highly detailed observations needed to address questions about prebiotic materials, as well as for observational needs mentioned by Dr. Meadows. Clear goals and a sustained development path will be essential to successful development of advanced telescopes. The Search for Earth-like Planets Roadmap will be key to keeping focused goals in mind. The roadmap must have a clear rationale for what it includes, so it can be revised and updated as circumstances change, rather than simply being abandoned. Interesting branch points will be important for sustaining interest over time.

In summarizing the responses from the members, Dr. Asrar noted that each had acknowledged the importance of sustainability, which is important for the entire science program at NASA. There will need to be exciting results attained in the near term, while building the foundations for long-term efforts. The rationales developed for the roadmaps will become the basis for advocating and explaining the program. At the same time, there will be challenges in building the basis for a sustained program, while also allowing for flexibility in responding to unexpected discoveries and external factors.

Ethics Briefing

Ms. Rebecca Gilchrist from the Office of the General Counsel, NASA Headquarters, provided the required ethics briefing for Special Government Employees (SGEs) serving on NASA advisory committees. SGEs are defined in Title 18 of the U.S. Code, which covers conflicts of interest of government employees. An Executive Order issued in 1989 listed general ethics principles for government employees, including SGEs. Among these principles are that public service is a public trust, employees may not have financial interests that conflict with their government roles, and employees must avoid even the appearance of impropriety. Status as a SGE is equivalent to being an insider, and SGEs are subject to civil service ethics rules and post-service restrictions. Ms. Gilchrist discussed provisions of Title 18 that prohibit representational activities before the Government and prohibit personal and substantial involvement, as part of the SGE's Government Service, in a particular matter before the Government. The prohibition applies if the matter involves parties (for example, a contract) and the SGE or his/her employer, spouse, or dependent child has a financial interest in that matter. Broad policy issues are not particular matters. She emphasized that members should have a feeling for what kinds of activities might need to be discussed beforehand with the Designated Federal Official for the committee or with counsel from the ethics team. If a committee member who is a SGE has a financial interest in a particular matter being discussed by the committee, the member should explicitly recuse himself/herself from the discussion. The meeting record for a public meeting should show when a member has recused himself or herself. Ms Gilchrist also described the waiver alternative to the recusal procedure.

Ms. Gilchrist described the post-employment restrictions under 18 USC 207, which pertain to making communications to the United States on behalf of another person, and the Standards of Conduct rules and exceptions on receiving gifts related to a SGE's official position. She provided contact information for ethics officials in the Office of General Counsel and emphasized the importance of conferring with the Designated Federal Official for the committee or a member of the NASA legal staff, if members have any questions concerning the ethics laws.

Session 1: Universe Division Context

Dr. Anne Kinney, Director of the Universe Division in SMD, spoke about the context of legacy activities relevant to this roadmap. She started with the committee's charter and the definition from the NASA Advanced Planning and Integration Office (APIO) of a strategic roadmap. It should be a coordinated, comprehensive longitudinal strategy that identifies key achievements, options, and decision point and provides a foundation for NASA's long-term priorities and investments. There will be a total of 13 strategic roadmaps prepared, responding to the 18 Agency-level strategic objectives. Essential elements of a strategic roadmap include broad science and exploration goals, priorities, recommended activities or investigations, and a summary of anticipated discoveries and achievements. It should suggest an approach for implementing the recommended activities, including mission sets. The time line presented in the strategy should include high-level milestones, options, and decision points. Key dependencies and relationships of this roadmap to other strategic roadmaps should be included, as well as required capabilities (technologies), facilities, human resources, and infrastructure.

Dr. Kinney compared the new planning process in NASA, which will use the strategic roadmaps as input, with the previous approach to strategic planning. Whereas the previous process was strictly bottom-up planning, the strategic objectives now provide top-down framing questions to which the roadmaps must respond. Integration of the strategic roadmaps and the 15 capability roadmaps into the Integrated Strategic Architecture (ISA) for the Agency will provide the basis for NASA's budgets, new initiatives, and Strategic Plan.

Before the NASA reorganization in August 2004, the former Astronomy and Physics Division had already begun the process of updating its legacy roadmaps for the Astronomical Search for Origins (Origins) and Structure and Evolution of the Universe (SEU) themes. Input from those roadmapping teams is the point of departure for the higher-level strategic view that the Search for Earth-Like Planets SRM Committee will provide. In response to a question, Dr. Asrar noted that the existing astrobiology roadmap is relevant to and will be captured in several of the strategic roadmaps, including this one. Dr. Kinney described the structural interfaces between the legacy roadmapping teams and the relevant SRM committees. She said that the legacy roadmaps on Origins- and SEU-related programs and projects will be combined in a Universe Division roadmap document, published for distribution in the science community. The Search for Earth-Like Planets SRM will have many points of connection with the Exploration of the Universe

SRM, and Dr. Kinney presented and discussed the membership of the Exploration of the Universe SRM Committee. She then described the guiding questions for the Universe Division's programs and presented the timeline for the operating missions and missions now in development. Major issues for the Universe Division include: (1) What, if anything is missing from the current program? (2) Has the community had adequate opportunity to provide input? (3) How is the division planning to mange its resources to address the strategic questions? (4) How should the currently operating missions and mission in development be split between the two strategic objectives directly related to the division's programs (the Search for Earth-Like Planets and the Exploration of the Universe objectives)? With respect to issues 2 and 3, she described the NASA Research Announcements (NRAs) in the past year for Vision Missions and Origins Probes concept studies, as well as the Einstein Probes included in plans for the Beyond Einstein Program.

At the co-chairs' request, Bernard Seery of the APIO provided additional context for the strategic roadmapping activities. NASA now has five Guiding National Objectives, which trace directly to the January 2004 document, *A Renewed Spirit of Discovery: The President's Vision for U.S. Space Exploration,* in which President Bush announced the Exploration Initiative. To implement these national objectives, NASA has formulated the 18 Agency-level strategic objectives for 2005 and beyond. The roadmaps are the strategies to achieve these strategic objectives. The ISA, which will provide the technical underpinning for NASA's strategic plan, must be flexible, affordable, and sustainable. It will be used to derive systems-level requirements, which will be passed to the NASA mission directorates for implementation through programs and projects.

The capabilities roadmaps cover the enabling technologies for the strategies. Due to timing constraints on budget formulation, NASA will be running the strategic and capabilities roadmapping activities in parallel through the summer of 2005. The ISA that results from their integration will feed into the update of the NASA Strategic Plan in fiscal year (FY) 2006. A team of systems engineers and program architects from inside NASA, as well as discipline scientists, will integrate all the roadmaps into the ISA. To support this integration process, each roadmap should include a priority set of activities/missions and the precedence relationships among roadmap elements. The APIO staff is already working on tabulating codependencies within and between roadmaps. The NRC will conduct a series of reviews to help guide the process. SRM committee co-chairs will act as a steering group for the integration process. The revised NASA Advisory Council will also have a role in reviewing the integration process. Mr. Seery emphasized that the ISA will serve as the decision framework that drives Agency decisions on programs and projects. In response to a question on how resource and funding constraints should be incorporated in the committee's work, he suggested that the committee work from the President's FY 2006 budget request as a guideline. He asked the committee to think about the key milestones over the next decade and the appropriate timing window for decisions dependent on those milestones. He suggested that detailed estimation of actual costs be left to the integration team, and he acknowledged that the committee will have to decide how best to include resource constraints in its deliberations. Dr. Asrar added that the committee should not necessarily take the current baseline as a given. The elements of the roadmap must be shown as integral components of a coherent, rational plan. However, the strategy should build from the current baseline. Mr. Seery agreed, adding that a compelling case for a roadmap element could result in it receiving higher priority in the integration process.

Session 2: Legacy Roadmap

Dr. Burrows discussed the status of the legacy roadmapping activities within the Universe Division. (A partial draft of material being considered for the legacy roadmap update was distributed to members of the Search for Earth-Like Planets SRM Committee as working papers, not for wider distribution.) The legacy teams are continuing their work of updating and merging the 2003 versions of the Beyond Einstein and Origins roadmaps. The full Universe Division subcommittee of the NASA Science Advisory Committee (NSAC) has not yet met to validate the full draft.

Dr. Burrows presented the outline of the Universe Roadmap and discussed in greater detail the chapters of most relevance to the Search for Earth-Like Planets SRM. The teams still need to incorporate and prioritize within the roadmap the Vision Missions from the 2004 concept studies and the Origins Probes concept studies. That subcommittee expects to meet in March. Dr. Burrows asked the members of the Search for Earth-Like Planets SRM Committee to read the draft and use portions as input for consideration, where relevant, for its roadmap. In response to a question on the future role of the competed Explorer and Discovery Programs, Dr. Asrar said that NASA will need a balance between focusing on NASA priorities and being open to innovative ideas from the science community. As in the past, the peer review process will be used to identify the best options. Members' comments on the importance of the research and analysis (R&A) program led to general discussion of issues in how best to provide support for R&A and theory studies within the Search for Earth-Like Planets SRM. Dr. Greene noted that the legacy version of the astrobiology roadmap also needs to be an input for the committee's use in its roadmap.

Session 3: Focused Discussions—Missions in Definition

James Webb Space Telescope

John Mather led the discussion on the relevance of JWST to planet finding. The JWST mission objective is to study the origin and evolution of galaxies, stars, and planetary systems. The four main science themes are (1) the end of the [universe] dark ages: first light and reionization; (2) the assembly of galaxies; (3) the birth of stars and protoplanetary systems; and (4) planetary systems and the origins of life. The program is now in the second year of its design, fabrication, assembly, and test phase, and the fourth JWST Science Working Group has been formed.

In his overview of JWST technology and architecture, Dr. Mather noted that it will orbit the L2 Lagrange point. He described the instruments that will be deployed with the telescope and said that the instrument teams are doing well with their designs. A video clip illustrated the sequence of events in deployment of the telescope after launch. Dr. Mather presented details of the mirror architecture, the choice of beryllium for the primary mirror composition, and the wavefront sensing and control system. He then focused on aspects of JWST capability relevant to studying the origins of habitable planets, including details of sensitivity and resolution for the fine guidance sensor, near infra-red camera (NIRCam), Mid-Infra-Red Camera (MIRI), and Near Infra-Red Spectrograph (NIRSpec). He also described JWST's high-contrast performance and the factors delimiting attainable contrast.

Discussion: In response to a question, Dr. Mather said that the tunable filters for the coronagraph are still in the JWST design and will be provided by Canada. In response to a question on single-point failures in implementation of the mission, he said that the deployment sequence and some other operations represent single-point failures. He described some of the tests needed as part of the risk reduction for these and other mission risks. The committee discussed the heritage JWST will create as a spacecraft operating in the vicinity of the L2 libration point and issues related to on-orbit repair of a telescope of this size.

The Kepler Mission and the Integrated Nature of Planet-Finding Missions

Dr. Zlatan Tsvetanov gave a briefing on the status of the Kepler mission and its place in the context of NASA's program for planet finding. He described the program as a succession of building blocks to accomplish the larger programmatic goal of searching for life outside the solar system. In this succession, Kepler, which is a Discovery-class mission, comes after work with ground-based interferometers—such as the Keck Interferometer and the Large Binocular Telescope Interferometer (LBTI)—and before the SIM and TPF missions.

Dr. Tsvetanov reviewed the four basic methods for indirect detection of extrasolar planets: radial velocities, astrometry, transit (of the planet across the stellar disc), and microlensing (of starlight by the planet's mass). Although radial velocity has been the method used in most detections to date, its limit of detectability is 18 Earth masses. The Kepler mission will survey a large sample of stars, detecting planets orbiting them by the transit method. Science objectives include determining the frequency of terrestrial and larger planets in or near the habitable zone of stars in a wide variety of spectral types, determining the size distributions and semi-major axes of the planets' orbits, and related objectives.

Kepler's primary mirror and the Schmidt collector plate are currently being polished. Kepler is the first implementation of a design in which a photometer comprising a large number of detectors is located in the focal plane of the telescope. Of 42 detector chip assemblies that will fly, 18 have been received. The project has successfully passed its preliminary design review (PDR) and confirmation review. It made the official transition to phase C/D on January 25, 2005. However, the project has been directed to absorb a $35 million cut and is currently working on a solution.

Discussion: Dr. Kinney, Dr. Tsvetanov, and the committee discussed the question of whether the results from Kepler on the frequency of planetary systems around the stars it surveys are needed to make decisions about the design of TPF-C. The answer may depend on whether metallicity in the spectrum of a star is a useful indicator for estimating the population of planets of approximately Earth size. In response to a question on the potential for false positives in Kepler's detection of planets, Dr. Tsvetanov described plans to use platform software and a catalogue of variable stars to eliminate false positives. This led to a discussion of ways that other platforms could be used to confirm positives indicated by Kepler. Dr. Smith asked about the importance, from the perspective of the overall planet-finding program, of Kepler's results establishing a value for the frequency of planets of near-Earth mass in the universe (η_{Earth}). Dr. Tsvetanov described the mechanisms for detecting such planets, and the committee discussed the contributions that various missions in the NASA and ESA programs will make to determining η_{Earth}. Dr. Tsvetanov noted that the difference between identifying Earth-size and Earth-like planets is critical, and only TPF will be able to do the latter. The committee and NASA staff discussed differences in science questions related to the ultimate goal of planet-finding, depending on how frequent Earth-like planets are in the observable universe. One issue is how to distinguish, for the public and lay audiences, between the partial information that Kepler (and other pre-TPF missions) will provide on candidates for an Earth-like planet and the information on the potential for bioactivity on these planets, which the TPF missions will provide.

Large Binocular Telescope Interferometer Science and Status

Dr. Philip Hinz of the University of Arizona briefed the committee on the LBTI. The project's goals include providing sensitive, nulling interferometric observations of nearby solar-like stars (the NIREST survey). It also will serve as a test bed for multipair nulling techniques, which can verify optical systems of the type needed for TPF-I. The telescope has primary apertures that are 8.4 m in diameter. The secondaries are adaptive mirrors, which perform the adaptive optics.

The NIREST survey will investigate about 80 stars for zodiacal dust disks and presence of gas-giant planets. Dr. Hinz described how LBTI will probe the dust limits for stars at up to 20 parsecs from Earth. He described results obtained to date with a prototype nuller on the Multiple-Mirror Telescope Observatory at Mt. Hopkins, Arizona, and the LBTI design requirements to accommodate Fizeau (wide-field imaging) interferometry. The first primary mirror for the LBTI is being tested now, and the adaptive secondary mirrors will be integrated into the interferometer structure in 2006. After showing photos and design graphics for various elements and subsystems in the LBTI, Dr. Hinz finished with a summary of the ways in which it provides a stepping stone and technology test bed for TPF-I.

Discussion: In response to committee questions, Dr. Hinz said that NASA's contribution to the LBTI installation cost is $5 million. The total cost for LBTI is $120 million, including 8 years of operation for the NIREST survey. Dr. Kinney added that she thought the total NASA commitment over LBTI's lifetime is $15 million. Ms. Heath asked if LBTI was of primary importance as a risk reduction demonstration of the nulling interferometry techniques, to which Dr. Hinz replied that it has an important science objective in providing an understanding of the limit zodiacal dust places on sensitivity of TPF-I. Both LBTI and the Keck Interferometer are needed to understand the zodiacal dust cloud limit around candidate stars, he said, because the two platforms observe different spectral regions of the dust cloud. Dr. Smith asked if there was a natural successor to LBTI in contributing to preparations for TPF, or does the NIREST survey do enough? Dr. Hinz answered that investigating other nulling techniques would be valuable. Dr. Beichman added that LBTI and Keck together provide a good foundation of ground-based interferometry to prepare for TPF.

<u>SIM, Keck Interferometry, and TPF</u>
Ms. Heath and Dr. Beichman recused themselves from discussion of SIM because of potential conflicts of interest.

Dr. Michael Shao of Jet Propulsion Laboratory gave a presentation on SIM, the PlanetQuest project, and TPF as an integrated approach to searching for and characterizing extrasolar planetary systems. He described the operational modes in which the Keck Interferometer has been or will be used. The Keck-Keck interferometry configuration has three operational modes: V^2, nulling, and differential phase interferometry. The Keck outrigger configuration can perform astrometry with approximately 30-microarcsecond resolution and imaging with a six-telescope array. The work to date has been done with the Keck-Keck modes of operation because of delays in environmental permitting for the outrigger telescopes, due to political and legal issues unrelated to the science. The aim of the astrometry is long-term monitoring to detect planets with long orbital periods. The time frame for detecting such planets is about one orbital period. Dr. Shao summarized the accomplishments to date with the V^2 interferometry and 10 μm nulling interferometry modes of the Keck–Keck configuration. He also discussed plans for use of the differential phase mode to detect hot Jupiter-like planets.

The SIM concept was first recommended in the 1990 NRC decadal survey and was reaffirmed as a priority in the 2000 decadal survey. The NRC Committee on Astronomy and Astrophysics endorsed it in 2002. A programmatic basis for SIM and TPF exists in both *A Renewed Spirit of Discovery: The President's Vision for U.S. Space Exploration* (January 2004) and NASA's response, *The Vision for Space Exploration* (February 2004). The planet-finding objectives for SIM and TPF include determining the architecture of planetary systems (numbers of planets and their masses and orbits); detecting terrestrial planets in the habitable zones around nearby stars, characterizing planetary atmospheres to search for signatures of life, and detecting and characterizing all the constituents of planetary systems to understand the context of habitable planets. During his description of the characteristics of planetary systems and planets that would be measurable by SIM and the TPF missions, Dr. Shao noted that both SIM and TPF are needed to get the full range of characteristics relevant to habitability. The Deep Search program for SIM will focus on about 250 stars like the Sun, located within 10 parsecs of the Earth. The SIM Broad Survey will sample 2,000 stars within 25 parsecs of Earth for planets with masses down to a fraction of one Jupiter mass. SIM will also provide information on the evolution of Jupiter-like planets and the implications for formation of Earth-like planets in stable orbits. Dr. Shao explained the ways in which Kepler and SIM have complementary roles in finding planets of near-Earth mass in the habitable zone of planetary system. The SIM Deep Survey will help to answer the question of what fraction of young stars have gas-giant planets and other questions about the parameters and evolution of these planets.

Dr. Shao next discussed the complementary and synergistic capabilities that SIM provides for detecting and characterizing Earth-like planets in the mission sequence of Kepler, SIM, TPF-C and TPF-I. SIM supports TPF by identifying a target list of planets most likely to maximize the science return from TPF. Whereas ESA's Gaia mission [planned for 2010-2012] will conduct a broad survey of stars, SIM will study fewer objects in much greater detail. Dr. Shao presented the SIM science team leaders and mission scientists and described the flight system architecture. The project has completed four system-level technology demonstrations in a microarcsecond test bed.. The latest two were a 1-microarcsecond narrow angle demonstration in September 2003 and a 4-microarcsecond wide angle demonstration in May 2004.The final technology milestone for NASA is modeling and test bed integration, which is scheduled for July 2005. On January 24, 2005, the project received a request from NASA to redesign the mission to reduce the estimated cost to between $1 and 1.2 billion. The project budget for FY 2005 was reduced by $15.1 million from earlier planning. The project is still working on an architecture redesign, after which the cost will be re-estimated.

The TPF-C science objectives include direct detection of Earth-like planets in the habitable zone of nearby F, G, and K type stars; measuring the frequency of Earth-like planets and their physical and orbital characteristics; and spectral characterization of their atmospheres in search of biomarkers such as oxygen, water vapor, and carbon dioxide. Dr. Shao reviewed the status of the coronagraph and interferometer technology needed for the TPF missions. ESA will take the lead on an interferometric TPF mission (called Darwin by ESA), which is planned to launch in 2015. Dr. Shao concluded with a discussion of what he expects will be known after Kepler, SIM, and the TPF missions have flown.

Discussion: Ms. Heath asked about the differences in science objectives of the ESA Darwin mission and TPF-I. Dr. Shao said they are the same mission. Dr. Tsvetanov noted that the Europeans want to accelerate Darwin to launch around 2015. In 2006, the current agreement on a planet-finding interferometer mission expires, and the degree of cooperation and collaboration on Darwin will be negotiated then.

Session 4: Critical Technologies

The Search for Earth-Like Planets SRM Committee heard status reports on two of the fifteen capability roadmaps being prepared in parallel with the strategic roadmaps.

Advanced Telescopes and Observatories Capability Roadmap
Dr. Lee Feinberg of NASA Goddard Space Flight Center (GSFC), a team co-chair, briefed the committee (via telephone) on the status of the Advanced Telescopes and Observatories Capability Roadmap. His capability roadmap team began meeting in November 2004. A draft of the

roadmap is due the week of February 21, with a presentation to an NRC review panel scheduled for March 15. The team began by developing a capability breakdown structure and organizing into six panels, which parallel that structure. The six capability areas are Optics, Wavefront Sensing and Control and interferometry, Distributed and Advanced Spacecraft Systems, Large Precision Structures, Cryogenic and Thermal Control Systems, and Infrastructure. Each area panel is led by an expert in the technical area. Among the inputs used by the team has been a list of reference missions provided by the SMD. This reference mission list will be reviewed by several of the strategic roadmapping committees. The reference missions related to planet-finding and the search for Earth-like planets have included TPF-C, TPF-I, and beyond that a life-finder mission and a planet-imaging mission. Dr. Feinberg requested that the Earth-like Planets SRM Committee inform his team if there are other missions the team should be considering. He described the sequence of meetings and milestones that have been completed or are coming up. There will be iterations of the capability roadmap draft during the spring, with a formal NRC review after that.

The Advanced Telescopes and Observatories Capability Roadmap Team has considered a number of potential vantage points in space for locating large optical systems. The L2 Lagrange point appears to be the overwhelmingly favorite location for future large space telescopes. The team has not yet received any reference mission input for a system that would be located on the Moon. A tentative conclusion on serviceability of a large scientific telescope system located at L2 is that servicing would only be cost-effective if the infrastructure for servicing exists for other reasons (e.g., to support human exploration objectives). A major theme of their work has been the improvements in telescope capabilities other than just increasing aperture size, such as contrast, precision, and for some systems (e.g., infrared telescopes), colder operating temperatures. In closing, Dr. Feinberg said he believes the team has a good understanding of what is needed in this capability roadmap to support the search for Earth-like planets through the time frame of the TPF missions. The mission concepts for future Life Finder and Planet Imager missions are not yet well defined. Alternative concepts for planet finding are represented in the roadmap only in general terms. He believes the team will be able to share a detailed draft roadmap with the SRM Committee in March.

Discussion: In answer to a question, Dr. Feinberg said he was not sure whether the Universe Division's Vision Mission concepts were included in the reference mission list. He suggested that the SRM committees (e.g., this committee and the Exploration of the Universe SRM Committee) should tell his panel which of the Vision Mission concepts to include for purposes of capability roadmapping.

Science Instruments and Sensors Capability Roadmap

Dr. Craig McCreight of Ames Research Center (ARC) briefed the committee (via telephone) on the work of the Science Instruments and Sensors Capability Roadmap Team. Dr. McCreight is co-lead for the subteam covering the visible, infrared, and far infrared (vis-IR-FIR) spectral range. He presented the charge to the roadmap team, which specifies that it identify critical capability gaps and assess future technology development needs in five areas: (1) active/passive microwave remote sensing; (2) multispectral imaging and spectroscopy; (3) laser and lidar remote sensing; (4) direct sensing of fields, waves, and particles; and (5) in situ measurements. To cover these areas, the roadmap team has set up six subteams, one for each of the areas except area 2, which has two subteams: multispectral imaging and spectroscopy in the visible, infrared, and far infrared; and multispectral sensing in the ultraviolet and gamma-ray spectral regions. The subteams are generally using instrument types to categorize capabilities within each subteam area, with component-level technologies as the next level of classification below instrument type. The team began meeting in December 2004. The February meeting included presentations by

Kathy Flanagan and Steven Murray from the Exploration of the Universe SRM Committee. The missions they specifically mentioned for the teams consideration were Constellation X, Laser Interferometer Space Antenna (LISA), a black hole finder mission, a black hole imager mission, Cosmic Microwave Background Polarization (CMBPol), Einstein Inflation Probe, Big Bang Observer, Joint Dark Energy Mission (JDEM), Single Aperture Far-IR Telescope (SAFIR), LUVO, Space Infrared Interferometric Telescope (SPIRIT), a submillimeter probe to investigate evolution of cosmic structure, TPF-C, TPF-I, and a life finder mission.

NASA Headquarters has provided the team with guidance on the hierarchy of sources it should reference as drivers for capabilities included in the roadmap. The hierarchy begins with documents or reports directly related to the Exploration Vision, followed by other directives from the President or the Office of Science and Technology Policy, NRC reports and recommendations, and legacy plans and reference missions from inside NASA. The reports from the Detector Working Group are being used as key technical resources. The Aerospace Corporation has created detailed spreadsheets for the science traceability of technology components, and the team has found these spreadsheets to be very useful for organizing capability data. An all-day presentation to an NRC panel is scheduled for March 17.

Dr. McCreight asked the Search for Earth-Like Planets SRM Committee to consider, from its perspective, whether his capability team has the right mission set. He also requested guidance on what the committee views as the priority missions for its roadmap. The approach taken thus far by the capability team has been to identify technologies with broad applicability, but also list other technologies that are key for specific missions or investigations. He stressed the importance of identifying linkages among his roadmap, other capability roadmaps, and the strategic roadmaps. Important infrastructure items include infrastructure for device fabrication, detector testing, and packaging.

Discussion. Dr. Burrows noted that generic names should be used in the roadmaps for missions that have not been named in an authoritative source such as an Agency directive or an NRC report. Names specific to a proposal or concept study should be replaced by a generic equivalent. The committee agreed on an **action item** to use the Enabling Technology chapter from the Universe Division legacy roadmap, prepared by Dr. James Breckinridge, as a technology input for the committee. A second **action item** was to get copies of the science traceability spreadsheets prepared by The Aerospace Corporation for the Science Instruments and Sensors Capability Roadmap.

Public Input Session 1

The meeting agenda included time for members of the public to provide input for the committee's consideration. For the first scheduled session, three visitors asked to make presentations to the committee and were granted time to do so by the co-chairs.

Roger Angel, University of Arizona
Dr. Angel began with a list of his key points and assumptions. He said that direct imaging is the preferred method for detecting the nearest examples of Earth-like planets, as well as being required for spectroscopic follow up. Therefore, direct imaging should be an overarching goal of the Search for Earth-Like Planets SRM. The main technological challenge for direct imaging is to detect a planet against the starlight halo. Achieving this will require a gain in imaging resolution of about 5×10^5 over current capability. For comparison, SIM represents just a factor of 1,000 improvement over classic astrometry. To meet the challenge in making improvements of this

magnitude, Dr. Angel believes that strong connections to the science community must be sustained.

Dr. Angel reviewed the physics of optical imaging as the basis for his approach for an interferometer located in the focal plane. By contrast, TPF-C is on a design path for an off-axis single mirror. He gave reasons why it may be more important to work on diffraction correction techniques, rather than perfecting the smoothness of mirror, and why a Hubble paradigm for TPF-C would be wrong. An effective solution for the inevitable figure errors may also resolve second order diffraction errors transparently. A segmented on-axis mirror may work just fine, he said. He then gave reasons for integrating the development of the telescope, point spread function (PSF) control, and science instruments to combine the functions of speckle phase sensing and the science imaging. His concluding recommendations were that NASA should coordinate with and support ground coronagraphy, just as it does with ground interferometry. In particular, NASA should consider large Antarctic telescope plans in coordination with a responsible roadmap for NASA planet-finding missions in space.

Mark Swain, NASA Jet Propulsion Laboratory and the Observatoire de Grenoble

Dr. Swain, who is on leave from JPL while working at the Observatoire de Grenoble, France, spoke about the potential for planet-finding science using Antarctic-based Interferometry and about activities in progress to realize that potential. Dr. Swain described the advantages of Antarctic sites, particularly the Concordia Station on Dome C, for interferometry. The elevation at Concordia Station is 3,200 meters, and the catabatic flow from this topographic high point results in a planetary boundary layer that is very close to the surface. Because of infrastructure already at Dome C, the Europeans are interested in using it for rapid deployment of interferometer technology. The new system can be packaged into modular instrument containers, which will function as assembly modules at the site. According to Dr. Swain, ice motion of the glacier on Dome C is a manageable challenge, as the shear velocity is on the order of 1 cm/km/year. A first step being discussed now in Europe is PARFAIT: the Partnership in Antarctic Research for Advanced Interferometry Techniques. In concluding, Dr. Swain emphasized ways that activities such as PARFAIT would fit with NASA objectives in searching for habitable-zone planets.

Marcia Rieke, University of Arizona

Dr. Rieke addressed the committee on the important of JWST and SAFIR as near- to far-infrared observatories for studying processes of planet formation. She emphasized the role of SAFIR as the follow-on mission for the Spitzer Space Telescope. All of the instruments for JWST have coronagraphic capability. The sensitivity in the 3.5 μm region of the Near IR Camera on JWST provides substantially more capability than either the Spitzer Space Telescope or ground-based telescopes. Dr. Rieke described other improvements for imaging distant galaxies that would be provided by SAFIR's increase in sensitivity, even assuming the same instrument capabilities as Spitzer. She summarized the contributions that JWST and SAFIR together can make to the study of planetary debris disks and planetary systems. The technology pieces for SAFIR are in place, she said, and the spacecraft and instruments could be developed for a 2015 launch date.

Discussion. Dr. Beichman noted that SAFIR was cited in the most recent NRC decadal survey as a priority mission. The committee discussed the decadal survey and other community documents supporting the importance of SAFIR.

Committee Discussion

Dr. Burrows asked the committee members for their thoughts on the presentations heard during the day and for any suggestions on additional information that should be brought to the committee's attention.

Ms. Heath said she was still working on understanding the relationships among all the pieces of the current planet-finding program. She suggested that some way to present the key relationships in a single chart would help. Dr. Beichman presented a graphic summarizing the current plan for advanced telescope searches for exoplanets, and the committee discussed how additional information on key relationships among missions could be incorporated in such a graphic.

Dr. Martin said that relatively little of what was presented had direct relevance to searching for Earth-like planets [as opposed to understanding the context of planetary system formation and evolution and the search for planetary systems in general]. The committee discussed how to have the roadmap focus on the missions that are central to the search for Earth-like planets, with other missions and investigations presented as supporting activities to this search. Dr. Beichman suggested a thematic structure using the three theme questions for the Universe Division, as noted by Dr. Kinney: How did the elements of life originate? Where do planets come from? Are there other habitable worlds? The committee discussed whether to take a broad versus narrow interpretation of the strategic objective to which this roadmap will respond. Dr. Martin suggested that a strong defense of JWST may not be necessary in this roadmap because of its central role in other areas covered by other strategic roadmaps.

Dr. Mather asked about an outline for the roadmap report and the schedule for preparing it. (These topics were addressed later in the discussion and in detail during the Wednesday sessions.). He suggested that the committee may need a summary of technological paradigm changes that can be expected or are required to meet the science goals of the roadmap.

Dr. Greene said it would be useful to consider the next level of definition below the three thematic questions for the Universe Division. He also thought that the roadmap should address how the Vision Mission concept studies and the Origins Probes studies fit into the thematic questions and the Search for Earth-Like Planets SRM.

Mr. Chodil said he was thinking about the technology challenges in meeting the science objectives and how to fill in the gaps between major missions in ways that provide risk reduction for the program while sustaining public interest.

Dr. Meadows asked about the role of ground-based programs in the roadmap. Dr. Burrows noted that NASA funding for LBTI and the Keck Interferometer was based on their role in developing interferometry techniques and technology for subsequent use in space-based missions. The committee discussed whether baselining advanced technology on the ground might be valuable to include in the roadmap, as preparation for capability to be used in space-based investigations.

Dr. Beichman presented a strawman outline for the roadmap, which he had based on the generic outline suggested for all the strategic roadmaps (discussed by Dr. Marc Allen on Wednesday morning). He also suggested chapter and section leads from among the members, as well as a tentative page budget. In closing for the day, Dr. Burrows asked the members to review the draft legacy roadmap chapters as a starting point for the committee's dialogue on the content of the roadmap. He summarized some of the topics relevant to roadmap structure and content that would be covered on the second day.

Wednesday, February 16

Federal Advisory Committee Act Briefing

Dr. Marc Allen gave the presentation for Diane Rausch, the NASA Advisory Committee Management Officer. He described the Federal Advisory Committee Act (FACA), Public Law 92-463, and its relevance to the committee's work. The strategic roadmap committees were chartered under FACA because it represents the "gold standard" for public access to external advisory processes in the executive branch of the Federal Government. There is a Government-wide limit, set by statute, on the number of FACA charters, which are administered by the General Services Administration. Each FACA committee must have a GSA-approved charter. The strategic roadmapping committees, which doubled the number of current NASA FACA committees, are chartered for a maximum of 15 months. Dr. Allen summarized the roles and responsibilities of the Advisory Committee Management Officer and the Designated Federal Official. The membership of advisory committees must be fairly balanced with regard to points of view represented and functions to be performed. The head of the Federal agency receiving the committee's advice appoints its members. Members who are not regular Federal employees may be either SGEs or representatives of special interests, and the SGE members must file the required financial disclosure forms. All of the non-Civil Service members of this committee are SGEs.

The objective of FACA is public access, not public participation. All deliberations that are aimed at reaching consensus on advice to the Government must occur in a public meeting. A quorum of half the members is required for a meeting. Meetings require public notice 15 days in advance, and the location must be accessible to the public. Committee information must be posted on the Internet. The public may submit documents or written statements; a FACA committee is not required to give visiting members of the public an opportunity to speak at the meeting. The circumstances under which a FACA committee can meet in closed session are strictly limited by the law.

Discussion. In response to a question on teams of committee members working on draft sections of text for consideration by the full committee, Dr. Allen said there was no difficulty with respect to FACA in drafting material that way. The full committee would be reviewing and deciding on the draft section in a subsequent public meeting. He discussed the conditions for a formal public teleconference as an option for the committee when it was deciding on responses to the NRC review of the draft roadmap.

Strategic Roadmapping Process

Dr. Allen, representing the APIO, briefed the Search for Earth-Like Planets SRM Committee on the strategic roadmapping process. He described what a strategic roadmap should contain, why NASA is doing them, how they will be used, and the schedule for the first round of roadmap development, review, and integration. A strategic roadmap is a coordinated, comprehensive longitudinal strategy that identifies key achievements, options, and decision points. It provides a foundation for making investments to achieve NASA's long-term priorities. There will be 13 strategic roadmaps prepared, plus 15 capability roadmaps. The foundation for the strategic roadmaps includes the five NASA Guiding National Objectives, as stated in *The New Age of Exploration: NASA's Direction for 2005 and Beyond.* This NASA document was released in February 2005 to support the President's FY 2006 Budget Request. Under these National Objectives are the 18 NASA Strategic Objectives for 2005 and beyond, which provide the specific direction to the strategic roadmap committees. In particular, the Search for Earth-Like

Planets Strategic Roadmap will implement Strategic Objective 4: "Conduct advanced telescope searches for Earth-like planets and habitable environments around the stars." Dr. Allen reviewed the Strategic Objectives assigned to each SRM committee and the co-chairs of the committees that are currently active. Each SRM committee has three co-chairs: one each from NASA Headquarters, a NASA Center, and outside the NASA organization. The capability roadmaps have been defined in terms of the technology capabilities identified in the Aldridge Commission report. They will be developed through several iterations to ensure their mutual consistency, as well as consistency with the strategic roadmaps.

Dr. Allen reviewed the historical context for the current process, starting with the report of the *Columbia* Accident Investigation Board (CAIB) in 2003, the President's announcement of the Exploration Vision in January 2004, and the Aldridge Commission report in June 2004. He described the new advanced planning function in NASA, which includes the Director for Advanced Planning and the APIO. The APIO provides staff support to both the Director for Advanced Planning and the Associate Deputy Administrator for Systems Integration. It is specifically tasked to work with the Mission Directorates and external advisory groups to coordinate development of strategies, roadmaps, and new initiatives. The purpose of roadmapping is to support creation of the NASA Integrated Strategic Architecture (ISA), which will ultimately be approved and owned by the NASA Strategic Planning Council. The strategic roadmaps and capability roadmaps will be integrated to form the ISA as a single, self-consistent multi-decade plan for the Agency. The ISA will be the benchmark for Agency budget requests and resource allocation decisions. Consistency in content and structure of the strategic roadmaps will be important in integrating them into an overall NASA architecture. Integration of the roadmaps will take into account overall constraints such as budget, technology readiness and science interconnections, programmatic factors such as institutional and community capabilities, and a range of "environmental" factors such as congressional views.

The new strategic planning process differs from the previous process in having Agency-level objectives to provide a framework for advanced planning in the Mission Directorates and in having the new level of APIO integration of roadmaps. The Agency-level objectives provide a set of top-down constraints to complement the bottom-up strategic planning done previously in the NASA Enterprises. The ISA will reflect the mission directorates' input through the roadmaps and the overall technical and programmatic integration by the APIO.

In response to a question from Dr. Martin on NRC reports relevant to the search for Earth-Like planets, planetary protection, and other issues relevant to shaping the roadmap and the ISA, Dr. Allen said that the NRC's response to the President's Vision for Space Exploration was available and the summary would be distributed to the committee. (This initial report from the Committee on the Scientific Context for Space Exploration, *Science in NASA's Vision for Space Exploration*, can be read on line or purchased at http://books.nap.edu/catalog/11225.html.) The committee discussed the historical background for a scientific focus on finding Earth-like planets. Communications from the NRC Committee on Astronomy and Astrophysics related to this emphasis in planet-finding will be distributed to the members. Dr. Burrows noted that a coronagraph TPF mission was not mentioned in the latest NRC decadal survey, which assumed that TPF would be an interferometer mission. The members discussed presenting the roadmap as an incremental, scientific approach to investigating planetary systems and realizing the ultimate goal of finding Earth-like planets.

Integration across the strategic roadmaps will be a major challenge, and Dr. Allen described how integration is running in parallel with the development of the individual roadmaps. The APIO coordinators will meet between the meetings of their committees to exchange information and coordinate roadmap-related activities. The aim is to capture the dependencies among the roadmaps, resolve overlaps and dependencies between the meetings, and incorporate them as explicit interfaces. A synthesis team will meet twice to formulate the content of the ISA from the completed strategic roadmaps and capability roadmaps. Integration of roadmaps into the ISA is planned for the summer of 2005.

The individual strategic roadmaps should establish priorities, options, and recommended approaches for achieving the NASA strategic objectives. Essential elements in each roadmap include a suggested implementation approach and mission sets to achieve the broad science and exploration goals. Each roadmap should identify high-level milestones, decision points, and options, as well as key dependencies on and relationships to the other strategic roadmaps. Dr. Allen presented a provisional outline that the strategic roadmaps should use as a starting point. The body of the roadmap report should begin with a statement of the strategic objective the roadmap addresses, followed by an overview of the objectives, stages (phases), and pathways (options) in the roadmap. Within this high-level framework, the report should then describe the recommended investigations, missions, R&D programs, etc., as the content of the framework. The report body, of about 30–40 pages, should focus on the objectives structure, phasing, and critical decision points. It should end with a summary of the key milestones, options, and decision points (pathway branch points). Graphics should be limited to a few key visualizations necessary for readers to understand the technical and programmatic structure of the roadmap. Dr. Allen listed a number of important supporting appendices, including capabilities required for the stages and pathway decision points, E/PO, opportunities unique to this roadmap, inter-roadmap dependencies, and external partnerships (Federal agency and international partners). One appendix should be a bibliography of supporting documents, including NASA documents and relevant reports from the NRC. Staff who are planning for NASA's human capital and facilities requirements to maintain core competencies have asked that the roadmaps address those needs as well. In response to a question on the primary audience for the roadmaps, Dr. Allen said that they will serve as technical input to the NASA staff on the synthesis team, which will develop the ISA.

The NRC will review the individual roadmaps as they near completion. Dr. Allen listed the questions posed to the NRC review panels and said the committee should take these review questions into account in preparing the roadmap. There will be mid-term internal reviews of the status of the roadmaps in mid-March. For the first synthesis workshop in late April, the committees need to provide a bullet-chart briefing with explanatory notes, not the full text of the roadmap report. The draft roadmaps are scheduled for submission to their NRC review panels by June 1, with the NRC reviews completed by August 1. The NASA Advisory Council will review the roadmaps in late August. The ISA is scheduled to be drafted by October 1, 2005. Dr. Allen discussed the Mars Next Decade investigation pathways as a model for the strategic roadmaps. This model includes pathway sequence options, with path decisions based on outcomes from near-term missions and investigations.

Mr. Bernard Seery, the APIO Director, provided additional context on the roadmapping process. The rollout of the President's Vision for U.S. Space Exploration means that NASA will be focusing in some new areas and conducting business differently than in the past decade. The Crew Exploration Vehicle (CEV) and heavy-lift launch vehicles to support the Exploration Initiative will be large-budget items. Current indications are that a launch vehicle capable of lifting 80 metric tons to low Earth orbit will be a key milestone objective. Work is already underway to focus the International Space Station (ISS) on human health and performance research and development with direct application to exploration objectives. There will be an ambitious robotic lunar program as a precursor to human missions to the Moon. The committee discussed the approach to take in the Search for Earth-Like Planets SRM to deal with these numerous pressures on the NASA budget, while advancing a strong case for the planet-finding program.

Session 5: Planet-Finding Science Goals and Objectives

NASA's Planet Quest Program

Dr. Beichman gave a presentation on the current planet-finding program as an integrated program to search for habitable planets and to understand the development of habitable environments. He introduced the presentation as a factual summary of the program as it is currently constituted. He began with the three thematic questions that Dr. Kinney has adopted for the Universe Division as defining NASA's response to the NASA Strategic Objective of conducting advanced telescope searches for Earth-like planets and habitable environments around the stars.

The committee discussed the scientific context for these three questions and, after discussion of the best way to present them in the roadmap, agreed to reverse their order to emphasize the close connection with the Exploration Vision. The committee also discussed how to present the role of JWST and other missions which overlap with the thematic question, "How did the universe become habitable?" and with the Strategic Objective assigned to the Exploration of the Universe SRM.

For the thematic question "Where do planets come from?", Dr. Beichman presented three key investigations: (1) What is the time scale for formation of gas giant and rocky planets? (2) What controls the orbital distribution of giant planets and how might their migration affect the formation and stability of terrestrial planets? and (3) How are the molecules of life brought onto barren rocky planets after these are formed? He then reviewed what Dr. Shao had said on Tuesday about the four projects within SIM that will result in a definitive planet census and the contributions to understanding of planet formation that can be anticipated from the Spitzer Space Telescope, JWST, Kepler, SOFIA, Herschel, and TPF-I.

For the question "Are there other habitable worlds?" (which will be the first of the questions addressed by the roadmap), Dr. Beichman said that planet detection will use both ground-based and space-based systems. He discussed approaches for seeking distant planets around young stars and seeking large and small planets in inner planetary systems (i.e., planets orbiting near the host star). The latter objective can be achieved using astrometry and radial velocity for nearby stars. Transit and microlensing can be used to find inner-system planets around distant stars. Dr. Beichman reviewed the interconnections and progressions in capability within the mission set that includes Kepler, SIM, TPF-C, and TPF-I. He listed reasons why a combination of TPF-C in the visible region and TPF-I in the mid-infrared gives better science results than either mission alone, enabling a robust search strategy for habitable planets. SIM will provide orbital parameters to identify planets in stable orbits within the habitable zone. The TPF and SIM missions together will provide information on terrestrial planet characteristics associated with habitability and planetary system characteristics needed for stable orbits in the habitable zone. The TPF missions will characterize indicators of life, including spectral evidence of biologically significant molecules and infrared characteristics of planetary atmospheres. For missions beyond current plans (i.e. beyond TPF-I), the technology that is needed but not yet developed must be addressed through adequate technology development programs.

JWST and SAFIR are clearly important as supporting missions to the main sequence of planet-finding missions, Dr. Beichman said. In addition, are there roles for smaller, competed missions, analogous to Kepler, through mechanisms such as the Discovery Program?

Discussion. The committee discussed how the lines of evidence from two or three missions would come together to confirm a discovery of an Earth-like planet and how this connectivity across missions could be presented in the roadmap. Dr. Beichman used Dr. Shao's slide on what will be known in 20 years, after Kepler, JWST, SIM, TPF-C, and TPF-I have flown, as another way of presenting the probable results from the integrated set of missions. Dr. Mather asked about decision points or mission results that could change the plan (i.e., create a branch point in the roadmap pathways). This led to general discussion of results from near-term missions that could influence the timing of and requirements for the TPF missions. In response to another question from Dr. Mather on potential *technological* branch points, Dr. Beichman said the program as currently planned has been designed to fit in existing launch vehicles. However, the design space for a post-TPF mission to search for signs of life on an Earth-like extrasolar planet may depend on what new launch vehicles are developed, as well as changes in other technology paradigms. Dr. Beichman suggested that budgetary decision points might also be needed in the roadmap. For example, should the roadmap include a slow-track option for a limited budget and a fast-track option if more resources are committed. Ground-based developments will also affect directions in the roadmap. The committee generally agreed that further thought will be needed on the branch points and controlling decisions to be incorporated in the roadmap.

Exoplanets: Known Properties and the Role of SIM and TPF

Dr. Geoff Marcy (who joined the meeting on the second day) began this presentation with a discussion of the radial velocity search for exoplanets, which to date has surveyed about 2,000 nearby hydrogen-burning starts (F, G, K, and M type stars). In this effort, periodograms of the velocity data have been used effectively o identify planets, their orbital periods, and their minimum masses. For the exoplanets identified by this search, the mass distribution in the range from Jupiter size to sub-Saturn size indicates that there are more planets at lower mass than at higher mass, at least for gas giants. No knowledge is yet available on the frequency and mass distribution of planets in the range of 1–15 Earth masses. A longer baseline of radial velocity observations will be needed to identify planets with periods greater than 10 years. There is evidence for significant populations of giant planets at 4 to 10 AU, similar to the orbital range of the gas giants in our solar system.

Orbital eccentricities are a major issue for dynamical stability of Earth-size planets. An open question is whether the low eccentricity of planetary orbits in our solar system is unusual or common in other planetary systems. Dr. Marcy cited some arguments implying that terrestrial planets at 1 AU should be plentiful. However, it appears that giant planets with nearly circular orbits are the exception in systems where they occur. Several radial velocity teams have found that the occurrence of planets orbiting a star correlates strongly with the abundance of heavy elements in the atmosphere of the host star. This result suggests that stars with an abnormal abundance of heavy elements are more likely to harbor giant planets. A reasonable supposition is that the formation of terrestrial planets, which presumably form by aggregation of dust particles during collisions, will also correlate with the metallicity of the host star. Of 140 known planetary systems, 17 are known to have at least two planets, 3 systems have three or more planets.

Next, Dr. Marcy discussed the role of SIM and the TPF missions in the search for Earth-like planets, framing his comments as a scientific response to the question, "Do we really need these missions, particularly SIM, to do planet finding, and are they worth the cost?" The goals of SIM are to determine the rate of occurrence of rocky, habitable planets within 25 parsecs of the Earth and characterize the mass, orbit, and chemical composition of the planets found. SIM and the TPF missions use the only methods that have been formulated and vetted thus far in the community for finding and characterizing terrestrial planets. Dr. Marcy does not see any additional strategies emerging that would be applicable within the next two decades. In response to a question, he agreed that SIM will not directly determine whether a planet is rocky. However, by combining orbital dynamics, the orbital characteristics of the planet, the host star's type, and the mass of the planet, a reasonable inference can be made about whether a planet characterized by SIM is terrestrial or gaseous. Dr. Marcy does not believe that theory alone, without the SIM and TPF missions, can be relied upon to answer the question of whether there are other Earth-like planets, their rate of occurrence, or their characteristics. Theoretical predictions about extrasolar planets have an abominable record, he said.

SIM will survey 250 dwarf stars of types A, F, G, K, and M within 15 parsecs, looking for planets of up to several Earth masses by astrometry. Planets of up to 3 times the Earth's mass will be identified with a confidence of 5 sigma. Planets of one Earth mass will be identified with a confidence of 1 sigma. These results will provide a short list of high-priority stellar targets for TPF (the stars most likely to have Earth-like planets). SIM will also provide orbital phase data to aid in timing and orienting the TPF observations. SIM therefore enhances the efficiency of TPF, and estimates of this enhancement range from threefold to tenfold. The estimate of 250 stars is based on the current allocation of SIM observing time to the two teams doing these observations. Doppler radial velocity reconnaissance of the target stars will be done prior to SIM, so the Jupiter- to Neptune-size planets will already be identified and their orbits characterized, within the limitations of radial velocity methods (detection limit of abut 0.2 Jupiter mass at 1 AU). SIM will make about 30 observations of each target star over a 5-year period.

The challenge for SIM astrometry, Dr. Marcy said, is to identify the six K-giant reference stars needed for observations of each target star. SIM's nominal "discovery space" around a host star is 3 to 30 Earth masses in orbits ranging from a few tenths of an AU to 1.5 AU. It will be able to determine the period, semimajor axis, and eccentricity of such planets. Simulations of SIM's detection capability, assuming 30 observations of planets with 1.5 and 3 Earth masses, show that the false alarm probability (expected frequency of false positives) is substantial enough that SIM results should be viewed as filtering the list of candidate targets for TPF-C to investigate and confirm.

Discussion. The committee discussed how the argument for SIM's value relative to TPF would be affected by different values of the rate of occurrence of Earth-like planets. Dr. Martin asked if the principal argument for SIM is its enhancement of TPF efficiency. Dr. Marcy replied that the significant technology challenges of TPF mean that SIM also needed to protect TPF-C from falling below its science floor. Dr. Beichman added that SIM gives the planet-finding program robustness and direct measurement of planetary masses, in addition to increasing the efficiency of the TPF missions. In summarizing his argument for the value of SIM, Dr. Marcy said one could call SIM the terrestrial planet *finder*, whereas TPF is the terrestrial planet *characterizer*. He ended with the additional value of SIM for other astrophysical investigations, as well as its role in enhancing the efficiency of TPF and reducing program risks. Dr. Burrows said that a consideration, which the committee could discuss at a later time, is that SIM has to meet a requirement of about 1 microarcsecond sensitivity to accomplish the objectives described by Dr. Marcy. If its capability were degraded by a descope to meet budget constraints, is there a point at which the mission would no longer be worth doing? (Dr. Beichman and Ms. Heath noted that they would need to recuse themselves from any discussion by the committee of the question Dr. Burrows had posed.)

Session 6: Coordination with Other Roadmaps

Mr. Rich Capps, the APIO coordinator for the Search for Earth-Like Planets SRM Committee, discussed the approach APIO is using to capturing interdependencies among the strategic and capability roadmaps. He sees definite linkages between this strategic roadmap and at least two others: the Exploration of the Universe SRM (SRM #8) and the E/PO SRM (SRM #12). Mr. Capps is also the APIO coordinator for SRM #8, so coordination with that activity is well covered. There are also potential linkages with SRM #5 on space transportation systems and SRM #13 on nuclear systems for space exploration. Dr. Smith suggested that the Search for Earth-Like Planets SRM may overlap with SRM #3 (Sustained Program of Solar System Exploration) on high data rate communications as a required technical capability. Dr. Meadows said that, based on the guiding strategic objectives, SRM #9 (Advance Scientific Knowledge of the Earth System) and SRM #10 (Explore Sun-Earth System to Understand the Sun and Its Effects) could have relevance to characterization of Earth-like exoplanets.

Mr. Capps cited strong dependencies between the Search for Earth-Like Planets SRM and three of the capability roadmaps: Capability Roadmap #3, advanced telescopes and observatories, which includes in-space construction and servicing by humans; Capability Roadmap #11, scientific instruments and sensors, which includes detectors, cryocoolers, and other technology subsystems of instruments likely to be used on planet-finding missions; and Capability Roadmap #13, advanced modeling, simulation, and analysis, which includes tools for testing spacecraft systems. The committee discussed whether Capability Roadmap #9, autonomous systems and robotics, and Capability Roadmap #14, systems engineering cost and risk analysis, might also be relevant to the Earth-like Planets SRM. Other possibilities mentioned were Capability Roadmap #4, communication and navigation, and Capability Roadmap #15, nanotechnology and advanced technology concepts.

As action items on inter-roadmap coordination, Dr. Burrows asked that the lists of strategic and capability roadmaps, together with supporting descriptions of their scopes, be distributed to the committee members. The members should review the information and send their suggestions on overlaps or dependencies, whether definite or potential, to Mr. Capps.

Session 7: Future Missions

Origins Probes

Dr. Eric Smith described the Origins Probes concept studies, which are in progress. The idea underlying the Origin Probes is that each probe mission would be smaller than a NASA flagship mission and similar in scope and cost to an Einstein Probes mission in the Beyond Einstein program. The NRA for the concept studies specified a $670 million mission cap, for launch in a 2015 time frame. The open competition resulted in nine awards. The Universe Subcommittee of the NSAC will review the concept studies and comment on which science objectives and technology capabilities from them are desirable to include in the Origins program. The studies will be completed in May, and their principal investigators (PIs) have given preliminary briefings to the Origins portion of the Universe Subcommittee.

Discussion. Mr. Chodil began a committee discussion on the value to the objectives of the Search for Earth-Like Planets SRM of a "directed" program of competitively selected small-missions. Members suggested several themes for Announcements of Opportunity in such a program that would be valuable for "filling in" the gaps among major missions in the planet-finding program. Examples mentioned included TPF precursors and searches for Jupiter-mass gas giants. Dr. Smith noted that a similar approach of thematic directions for competitively selected missions was incorporated in the Einstein Probes, which have three defined mission areas.

Universe Division Vision Studies

Dr. Marc Allen described the background to the Vision Mission concept studies. The Office of Space Science (predecessor to the SMD) was interested in looking further out than the 10- to 15-year window of its current design reference missions. The objective is to provide a representative baseline of long-term mission concepts, not to make a decision on which concepts would move forward as future missions. The announcement of the competition was issued as an appendix to the annual Research Opportunities in Space Science NRA (ROSS, now the Research Opportunities in Space and Earth Sciences, or ROSES). Awards were made for studies that addressed any of the long-term mission possibilities mentioned in the 2002 theme roadmaps of the Office of Space Science. Awards of about $310,000 each were made for 15 proposals, distributed among the Space Science themes. The first of the reports should be completed in several months. Their PIs have briefed the advisory subcommittees of the Space Science Advisory Committee (a predecessor to the NASA Science Advisory Committee). Dr. Allen is giving the study teams a template to follow for their final reports.

Discussion. Members asked for brief (one page) summaries of the concept studies. Dr. Burrows said there are two aspects of the vision missions activity that should be considered by the committee. One aspect is the general concept of doing these kinds of concept studies to define a baseline of mission possibilities. The second aspect is the specific set of vision missions defined by the studies being done in this round. Dr. Mather added that astrobiology is another topic for which long-term concept development is needed and which is relevant to the Search for Earth-Like Planets SRM, as well as to other SRMs. Dr. Smith said that the current astrobiology program in SMD is managed out of the Solar System Exploration Division. The latest ROSES announcement includes calls for both traditional astrobiology interdisciplinary topics that have an astrobiology component. Dr. Greene reiterated his earlier point that the committee should review the latest astrobiology roadmap to see which parts are relevant for the Search for Earth-Like Planets SRM. The members discussed aspects of an astrobiology program that are needed for the search for Earth-like planets.

Public Input Session

There were no requests at this time from members of the public attending the meeting to provide input to the committee.

Planning for Next Meeting and Roadmap Drafting Assignments

Dr. Burrows led the committee in discussing the schedule for its second meeting. There was general agreement to hold open the window of March 29–31, with March 29–30 as the best option for a two-day meeting.

Dr. Beichman led a discussion of his strawman outline for the roadmap report. Dr. Martin suggested that the story line for chapter 3 focus on risk reduction and technology development specific to the goal of finding Earth-like planets. The committee generally agreed with his suggestion that a systems-engineering style of argument for the planet-finding program as a series of interdependent components was desirable. Dr. Burrows reminded the members to review the draft legacy roadmap for the Universe Division and select topics and text that could be useful for the Search for Earth-Like Planets SRM.

The committee then returned to a detailed discussion of Section III in Dr. Beichman's strawman outline. There was agreement to rearrange the sequence of topics in that section. The committee discussed how to strengthen the relationship between Sections II and III to be comprehensive while maintaining a compelling story. Another topic discussed was whether a section focusing on education and public outreach should be in the report body or an appendix.

Members assigned to draft material for Section II were Meadows, Weinberger, Marcy, Mather, and Spergel. The committee discussed missions whose role in supporting planet-finding should be introduced in the Section II discussion of the theme, "How did the universe become habitable?" There was agreement to include JWST and SOFIA in this discussion. In response to Dr. Smith's question about including the Hubble Space Telescope (HST) as a supporting mission, the committee discussed the extent to which HST has played a role and how it could contribute to supporting the main planet finding missions, if it remains operational into their operational life times. Potential downsides of appearing to advocate a follow-on Hubble-like mission were raised as well, particularly with respect to possible impacts on resources for missions in the main roadmap pathway.

Dr. Martin agreed to serve as the lead for Section III, with contributions from Mather, Chodil, Greene, Meadows, Marcy, and Heath. Section IV will be drafted by Drs. Beichman and Martin, with support from Michael Devirian. Dr. Edna de Vore will act as lead for compiling material for Section V, with the aid of Dr. Neil Tyson. A draft of Appendix 3 is also needed by the March meeting. Dr. Smith will assemble a document list and Internet unique resource locators (URLs) for Appendix 5. Key enablers, including technology development, will be covered in summary form in section IV, as well as being detailed in Appendix 2. The team working on the draft for a section can choose to reorganize it. Dr. Beichman agreed to revise the outline to incorporate the prior comments from the members and send it out to the entire committee. He will also send out a timetable for integrating the pieces of each section and distributing the sections to all the committee members prior to the second meeting. Dr. Smith will send all the committee members information on using the committees document-sharing website. He will make available on that website or otherwise distribute to the members the electronic versions of the presentations from Drs. Beichman and Shao, as well as contact information for all committee members and support staff. Dr. Burrows will distribute a Microsoft Word version of the Universe Division legacy roadmap draft to the committee in a week or so.

The meeting was adjourned at 3:40 p.m. MST.

Search for Earth-like Planets Strategic Roadmap Committee
February 15–16, 2005
Westward Look Hotel
Tucson, Arizona

Agenda

Tuesday, February 15

8:30 a.m.	Continental breakfast	
9:00 a.m.	Meeting Opening Convene Meeting Introduction of Committee Members Objectives/Charter/Expectations (Planet finding/study in 2035)	 (Roadmap Chairs)
10:00 a.m.	Ethics briefing	(Rebecca Gilchrist)
10:30 a.m.	Session 1: Universe Division Context Review of existing programmatic matters	 (Anne Kinney)
11:00 a.m.	Session 2: Legacy Roadmap Community Legacy Roadmap Status	 (Adam Burrows)
12:00 p.m.	Lunch	
1:30 p.m.	Session 3: Focused Discussions – Missions in Definition James Webb Space Telescope (JWST) Kepler Large Binocular Telescope Interferometer Space Interferometry Mission (SIM) and Keck Interferometry Terrestrial Planet Finder (TPF)	 (John Mather) (Zlatan Tsvetanov) (Philip Hinz) (Mike Shao) (Mike Shao)
3:00 p.m.	Session 4: Critical Technologies Architectural Drivers Required Technologies	 (Lee Feinberg, Craig McCreight)
4:00 p.m.	Public Input session 1 Committee Discussion First day wrap-up and overnight assignments	

Wednesday, February 16

8:30 a.m.	Continental breakfast	
9:00 a.m.	Strategic Roadmapping Process	(Marc Allen)
	Federal Advisory Committee Act briefing	(Diane Rausch)
10:30 a.m.	Session 5: Planet Finding Science Goals & Objectives	
	Planet Finding: Prehistory to Today	(Geoff Marcy)
	NASA's Planet Quest Program	(Charles Beichman)
12:00 p.m.	Lunch	
1:30 p.m.	Session 6: Coordination with other Roadmaps	
	Relationships to other strategic roadmaps (Universe Division, Solar System Exploration, Earth-Sun system, Education)	(Panel Chairs)
2:00 p.m.	Session 7: Future Missions	
	Vision Missions, Probes, Life Finder, Planet Imager, etc.	(TBD)
2:30 p.m.	Public Input session 2	
	Planning for next meeting	
	Roadmap outline, assignments	(Charles Beichman)
3:30 p.m.	Committee Discussion	

Search for Earth-like Planets Strategic Roadmap Committee
Committee Roster

Ghassem Asrar *co-chair*
Deputy Associate Administrator, Science Mission Directorate, NASA

Charles Beichman, *co-chair*
Jet Propulsion Laboratory

Adam Burrows, *co-chair*
University of Arizona

Gerald Chodil
Ball Aerospace (*retired*)

Alan Dressler
Carnegie Observatories

Tom Greene
NASA Ames Research Center

Maureen Heath
Northrop Grumman Space Technology

Geoff Marcy
University of California, Berkeley

Frank Martin
Lockheed Martin (*retired*)

John Mather
NASA Goddard Space Flight Center

Victoria Meadows
Jet Propulsion Laboratory

David Spergel
Princeton University

Neil Tyson
American Museum of Natural History

Alycia Weinberger
Observatories of the Carnegie Institution of Washington

Rich Capps
APIO Coordinator
Jet Propulsion Laboratory

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Search for Earth-like Planets Strategic Roadmap Committee
February 15–16, 2005
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MEETING ATTENDEES

Committee Members:

Asrar, Ghassem, *co-chair*	NASA Headquarters
Beichman, Charles, *co-chair*	NASA/JPL
Burrows, Adam, *co-chair*	University of Arizona
Chodil, Gerald	retired
Greene, Tom	NASA Ames Research Center
Heath, Maureen	Northrop Grumman Space Technology
Marcy, Geoff	University of California, Berkeley
Martin, Frank	retired
Mather, John	NASA Goddard Space Flight Center
Meadows, Victoria	NASA/JPL
Smith, Eric, *Designated Federal Official*	NASA Headquarters

NASA Attendees:

Allen, Marc	NASA Headquarters
Devirian, Michael	NASA/JPL
Breckinridge, Jim	NASA/JPL
Capps, Rich	NASA/JPL
Gilchrist, Rebecca	NASA Headquarters
Hasan, Hashima	NASA Headquarters
Heap, Sara	NASA/GSFC
Kinney, Anne	NASA Headquarters
Oegerle, William	NASA/GSFC
Seery, Bernard	NASA Headquarters
Shaw, Mike	NASA/JPL
Swain, Mark	NASA JPL/ “U of A”
Thronson, Harley	NASA Headquarters
Tsvetanov, Zlatan	NASA Headquarters

Other Attendees:

Angel, Roger	University of Arizona
Katt, Robert	INFONETIC
DeVore, Edna	SETI Institute (*ex officio* member of the SRM committee)
Fischer, David	Ball Aerospace
Friedman, Ed	Boeing
Martin, Pam	self
Rieke, Marcia	University of Arizona

Search for Earth-like Planets Strategic Roadmap Committee
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LIST OF PRESENTATION MATERIAL[1]

1. NASA Office of General Counsel. *Ethics Briefing for Special Government Employees Serving on NASA Advisory Committees.*
2. Anne L. Kinney, Director, Universe Division, Science Mission Directorate, NASA. *Universe Division Perspective*.
3. Adam Burrows. *Status of the Universe "Legacy" Roadmap. A Merger of the Origins and SEUS/Beyond Einstein Programs.* February 15, 2005.
4. NASA. Draft of 2005 Universe Roadmap. File RdMp40.doc. February 14, 2005. (working draft distributed to Earth-like Planets SRM Committee for information and comment).
5. Zlatan Tsvetanov, TPF Program Scientist, NASA Headquarters. *NASA Planet Finding Program.*
6. Lee Feinberg, NASA Goddard Space Flight Center, and Howard MacEwen, SRS/NRO. *Advanced Telescopes and Observatories Capability Roadmap. Status Presentation to Search for Earth-like Planet Strategic Panel.* February 15, 2005.
7. Craig McCreight, Vis-IR-FIR subteam co-lead, Capability Roadmap Team #12. *Science Instruments and Sensors Capability (Team #12) Roadmap Activity*. *Status Report to Strategic Team #4*. February 15, 2005.
8. Mark Swain. *Antarctic Interferometry Potential.* February 2005.
9. *Strategic Roadmap Search for Earthlike Planets.* Presentation by Roger Angel, Tucson, February 15, 2005.
10. Marcia Rieke, NIRCam for JWST Principal Investigator. *JWST and SAFIR: Near- to Far-Infrared Observatories for Origins*.
11. Marc S. Allen, Advanced Planning and Integration Office. *NASA Strategic Roadmaps*. *Briefing to the Search for Earth-like Planets Strategic Roadmap Committee*. 16 February 2005.
12. P. Diane Rausch, NASA Advisory Committee Management Officer. *Federal Advisory Committee Act. Presentation to Search for Earth-like Planets Strategic Roadmap Committee. First Meeting, Tucson, AZ.*
13. Charles, Beichman, Michelson Science Center. *An Integrated Program to Search for Habitable Planets and to Understand the Development of Habitable Environments.* February 16, 2005.
14. Geoff Marcy et al. (members of the SIM Science Team). *Exoplanets: Known Properties and the role of SIM/TPF*. NASA Strategic Roadmap Committee, Tucson, 11 January 2005.
15. Rich Capps, Advanced Planning and Integration Office, NASA. *Search for Earth-like Planets. Roadmap Integration Interdependencies: Preliminary.* February 16, 2005.

[1] Presentation and other materials distributed at the meeting are on file at NASA Headquarters, Science Mission Directorate, Washington, DC 20546. For access, contact Dr. Eric Smith, the Designated Federal Official.